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13. ABSTRACT *(Maximum 200 words)*

The objective of the research under this ONR award is to develop distributed multisensor data fusion algorithms for tracking applications, as well as non-simulation and analytical methods of performance evaluation. Since the beginning of this project in June 1997, we have achieved results in several different areas: (1) We have developed a method of distributed fusion that is amenable to general distributed architectures; (2) We have developed two non-simulation techniques for comparing multisensor probabilistic data association filters that are significantly more computationally efficient than performing Monte Carlo simulation evaluations; (3) We have investigated and compared the computational complexity and tracking performance of sequential and parallel implementations of the multisensor probabilistic data association algorithm; and (4) We have developed several schemes for controlling sensor information and have evaluated the effects of delays. Our results will provide insight as to the relative performance of various multisensor fusion methods, and the results will also provide a basis for assessing the tradeoffs between performance and computational and communication requirements when planning new sensor network architectures or communication link protocols.

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Young Investigator Award:
Distributed Multisensor Fusion Algorithms for Tracking Applications
(ONR Grant N00014-97-1-0642)

Annual Report, May 1998

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A brief summary of the progress made in research under this Young Investigator Award is given here. The following papers, funded fully or partially under this ONR award, were published or submitted and are attached.

[A] L. Y. Pao and M. K. Kalandros. "Algorithms for a Class of Distributed Architecture Tracking," *Proc. American Control Conf.*, Albuquerque, NM, pp. 1434–1438, June 1997.

[B] C. W. Frei and L. Y. Pao. "Alternatives to Monte Carlo Simulation Evaluations of Two Multisensor Fusion Algorithms," *Automatica*, 34(1): 103–110, Jan. 1998.

[C] M. K. Kalandros and L. Y. Pao. "Controlling Target Estimate Covariance in Centralized Multisensor Systems," *Proc. American Control Conf.*, Philadelphia, PA, June 1998, in press.

[D] L. Y. Pao and M. K. Kalandros. "The Effects of Delayed Sensor Requests on Sensor Manager Systems," *Proc. AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, Aug. 1998, in press.

Other related papers that were submitted or published include:

[E] L. Y. Pao, T. N. Chang, and E. Hou. "Input Shaper Designs for Minimizing the Expected Level of Residual Vibration in Flexible Structures," *Proc. American Control Conf.*, Albuquerque, NM, pp. 3542–3546, June 1997.

[F] L. Y. Pao and W. E. Singhose. "Verifying Robust Time-Optimal Commands for Multi-Mode Flexible Spacecraft," *AIAA J. Guidance, Control, and Dynamics*, 20(4): 831–833, July-Aug. 1997.

[G] L. Y. Pao. "An Analysis of the Frequency, Damping, and Total Insensitivities of Input Shaping Designs," *AIAA J. Guidance, Control, and Dynamics*, 20(5): 909–915, Sept.-Oct. 1997.

[H] L. Y. Pao and W. E. Singhose. "Robust Minimum Time Control of Flexible Structures," *Automatica*, 34(2): 229–236, Feb. 1998.

[I] L. Y. Pao and D. A. Lawrence. "Synergistic Visual/Haptic Computer Interfaces," *Proc. Japan/USA/Vietnam Workshop on Research and Education in Systems, Computation, and Control Engineering*, Hanoi, Vietnam, pp. 155–162, May 1998.

[J] L. Y. Pao and Craig F. Cutforth. "An Analysis and Comparison of Frequency-Domain and Time-Domain Input Shaping," *Proc. American Control Conf.*, Philadelphia, PA, June 1998, in press.

[K] L. Y. Pao and M. A. Lau. "Input Shaping Designs to Account for Uncertainty in Both Frequency and Damping in Flexible Structures," *Proc. American Control Conf.*, Philadelphia, PA, June 1998, in press.

[L] L. Y. Pao and M. A. Lau. "An Analysis of the Expected Residual Vibration of Input Shaping Designs," *Proc. AIAA Guidance, Navigation, and Control Conf.*, Boston, MA, Aug. 1998, in press.

[M] D. A. Lawrence, L. Y. Pao, A. M. Dougherty, Y. Pavlou, and S. W. Brown. "Human Perceptual Thresholds of Friction in Haptic Interfaces," *Proc. 7th Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, to be held at the *ASME Int. Mech. Engr. Cong. & Expo.*, Anaheim, CA, Nov. 1998.

[N] L. Y. Pao. "Multi-Input Shaping Design for Vibration Reduction," accepted for publication in *Automatica.*

[O] L. Y. Pao and M. A. Lau. "The Expected Residual Vibration of Traditional and Hybrid Input Shaping Designs," submitted in Jan. 1998 for publication in the *AIAA J. Guidance, Control, and Dynamics.*

[P] L. Y. Pao and M. A. Lau. "Minimal Expected Residual Vibration Input Shaping Designs for Flexible Structures," submitted in Mar. 1998 for publication in the *ASME J. Dynamic Systems, Measurement, and Control.*

[Q] D. A. Lawrence, L. Y. Pao, A. M. Dougherty, M. A. Salada, and Y. Pavlou. "Perceptual Hardness: A New Performance Metric for Haptic Interfaces," submitted in May 1998 for publication in the *IEEE Trans. Robotics and Automation.*

Research Activities

The objective of the research under this ONR award is to develop distributed multisensor data fusion algorithms for tracking applications, as well as non-simulation and analytical methods of performance evaluation. We are addressing the estimation and data association process, where different measurement types must be integrated into one common estimation process, and consistent probability metrics must be established for all sensor types. In developing various algorithms, we are focusing our work and results to be useful for Naval tracking and surveillance systems.

Since the beginning of this project in June 1997, we have achieved results in several different areas:

- Multisensor target tracking is often performed using a single processor to monitor several sensors (centralized fusion), but this method is demanding of both computational power and communication bandwidth. Distributed sensor fusion is a method of addressing these limitations. However, the distributed sensor fusion problem is more complex due to the correlation of separate track estimates. We previously developed a method known as measurement reconstruction and showed that it addresses this correlation problem in a specific class of distributed architectures [1]. We have extended the measurement reconstruction approach to a more generalized architecture using two new algorithms [A]. Computational and communication requirements have been compared with centralized sensor fusion, and Monte Carlo simulation studies have been used to compare the performance of these and other algorithms. We are currently investigating the robustness of our algorithms to modeling errors that can yield errors in the measurement reconstruction process.

- Because Monte Carlo simulation evaluations of multisensor multitarget tracking algorithms is time consuming and expensive, we have developed two non-simulation techniques for comparing multisensor probabilistic data association filters (MSPDAF) [B]. While requiring only a fraction of the time for Monte Carlo simulation evaluation, the non-simulation techniques have been shown to accurately predict the performance of the MSPDAF in terms of RMS position error and track lifetime which has been observed in simulations.

- We have investigated and compared the computational complexity and tracking performance of sequential and parallel implementations of the multisensor probabilistic data association algorithm [B]. Our studies indicate that the sequential implementation is better on the average than the parallel implementation, in terms of both RMS position error and track lifetime metrics. We have further developed analytical results that show that the sequential implementation is exponentially more computationally efficient as the clutter density and number of sensors increase. We are currently investigating how the order of processing sensors in a sequential implementation affects tracking performance.

- Using multiple sensors in surveillance systems allows the strengths of one sensor type to compensate for the weaknesses of another and further provides redundance, therefore increasing system robustness. However, because multiple sensors in many surveillance systems provide more information than can be processed with the available computational resources, we have developed several schemes for controlling sensor information. In order to keep the mathematics more tractable in our initial work [C], we have assumed a centralized processing architecture, where the measurements from all sensors are sent to a global processor where the measurements are fused and used for estimating the states (position, velocity, etc.) of the objects in the surveillance region. We have developed three algorithms that maintain a target's state estimate covariance near a desired level without over-taxing the computational resources of a tracking system. We have also modeled and evaluated the effects that (inevitable) delays can have on performance [D]. Current work is focused towards extending results to decentralized multisensor systems.

Our results will provide insight as to the relative performance of various multisensor fusion methods, and the results will also provide a basis for assessing the tradeoffs between performance and computational and communication requirements when planning new sensor network architectures or communication link protocols.

[1] L. Y. Pao. "A Measurement Reconstruction Approach for Distributed Multisensor Fusion," *AIAA J. Guidance, Control, and Dynamics*, 19(4): 842–847, July-Aug. 1996.